Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 147 (2016) 62 – 67

Procedia Engineering

www.elsevier.com/locate/procedia

11th conference of the International Sports Engineering Association, ISEA 2016

A new wind tunnel facility dedicated to sports technology research and development

Mikael Bäckström*, Peter Carlsson, Jonas Danvind, Andrey Koptyug, David Sundström, Mats Tinnsten

SportsTech Research Centre, Mid Sweden University, Akademigatan 1, 831 25 Östersund, Sweden

Abstract

It is desirable to test sportswear and sports equipment at exactly the same conditions experienced during use. Although outdoor tests are in many cases the most adequate, they are at the same time quite complex, demand special measurement technology and wearable equipment. Results of such tests are often hard to interpret due to large variations because of rapidly varying ambient conditions and individual specifics of human objects, among other factors, which are hard or impossible to control. One common alternative is provided through indoor tests made in a stable, controlled environment.

Controlling such parameters as temperature, wind speed and direction, air humidity with indoor facilities intended to replicate ambient conditions, and designed to house large objects, is a complex undertaking. Furthermore, replicating seasonal conditions complicates matters even more. A significant amount of research and development related to the operation of sports and other related equipment at high speeds and windy conditions has been carried out in wind tunnels with different degrees of climatic realism. However, the majority of such facilities are designed and constructed for the automotive industry, the aerospace industry and for marine research. A new wind tunnel facility, opened in March 2015 at the Sports Tech Research Centre at Mid Sweden University, is currently among the very few facilities in the world designed under the direct control of sports technology specialists and dedicated primarily to research and development within sports, outdoor clothing and footwear as well as equipment development and testing.

The main goal when constructing this dedicated facility has been to successfully replicate ambient conditions for training and equipment testing in environments with controlled wind speed, temperature (+4 to +35 ^{o}C) and precipitation (from fine mist to heavy downfall). The wind tunnel facility houses the largest moving belt in Sweden (5 m long and 2.7 m wide) which can be adjusted for leveled, uphill and downhill motion. The moving belt is placed in a 10 m^2 test section in which the wind speed can be adjusted to match belt speed or independently up to 55km/h (without narrowing the test section). A fog and rain system, mounted in the test section, can generate rainy conditions varying from fine mist to heavy monsoon. It is also possible to open the facility in order to allow experiments to be performed in wide range of outdoor, ambient conditions.

This paper presents the basic parameters of the new wind tunnel facility. As this facility is open for wider international cooperation, we also report the general directions of current research and the future work planned to be carried out at this facility.

Peer-review under responsibility of the organizing committee of ISEA 2016

*Keywords:*wind tunnel; climate control; moving belt; product development; indoor testing

1. Introduction

Realistic testing of new garments, footwear and equipment for sports and outdoor activities is a challenge designers, researchers and industry are constantly facing. Outdoor tests are considered to be the most realistic but are at the same time quite complex to perform, depending on multiple or hard to control factors. Gathering field data demands special protocols and special, often lightweight and wearable, measurement equipment not affected by vibrations and varying ambient conditions such as temperature or humidity. One common alternative is provided through indoor tests made in a stable, controlled environment.

* Corresponding author. Tel.: +46-63-165501; fax:+46-63-165500.
*E-mail address:*Mikael.Backstrom@miun.se

Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.190

However, even with indoor facilities intended to replicate the ambient conditions needed for testing, controlling such parameters as temperature, wind or humidity is a complex undertaking even with small to medium-sized climatic chambers or wind tunnels designed for testing small-scale objects [1, 2]. As it is often very difficult, or even impossible, to adequately represent the whole test object as a sum of separate, smaller parts - especially when it is tested separately from the humans that will be using it. Therefore, it is desirable to have a laboratory facility mimicking, as closely as possible, a desired set of ambient conditions, while at the same time being large enough to simultaneously accommodate the test objects and the necessary measurement equipment.

A significant amount of research and development related to the behavior of different test objects and equipment at close to ambient conditions is carried out in "climatic" wind tunnels. Most current facilities are designed and constructed for automotive, aerospace and marine sector research and are developed with their specific demands in mind. Some years ago the decision was taken at Mid Sweden University to construct a test facility designed under the direct control of sports technology specialists and dedicated primarily to research and development within sports and related technologies. It was decided that this facility should primarily help boosting research and development within existing programs at the Sports Tech Research Centre but should also support the local and national industries oriented towards the sports and outdoor clothing, and footwear and equipment markets.

Sports technology research and development at the Sports Tech Research Centre is traditionally dedicated to winter activities and bicycle sports, but also involves equipment for the disabled and systems for field measurements. Therefore, from the very beginning, it has been clear that this new wind tunnel facility should have unique layout and parameters, and house a relatively large, flexibly-controlled moving belt. Being of interest to both winter and summer activities, it was presumed that the facility would require replicating a reasonably wide range of ambient conditions, including both low (winter) and high (summer) temperatures along with controlled levels of wind and precipitation.

2. Basic design of the wind tunnel facility

The wind tunnel laboratory at the Sports Tech Research Centre, designed with the help from our colleagues at Loughborough University, can be set to either a closed-circuit or atmospheric air inlet configuration (Fig. 1a).A dedicated brick building (10) houses the wind tunnel, together with the service units and laboratories, and is approximately 10m wide, 8m high and 23m long. The working part of the tunnel has double Lexan walls. The area (2) between the inner walls (3) and the outer corridor (1) is protected from the wind and provides space for equipment and service personnel ("calm corridor"). Air enters the test section that

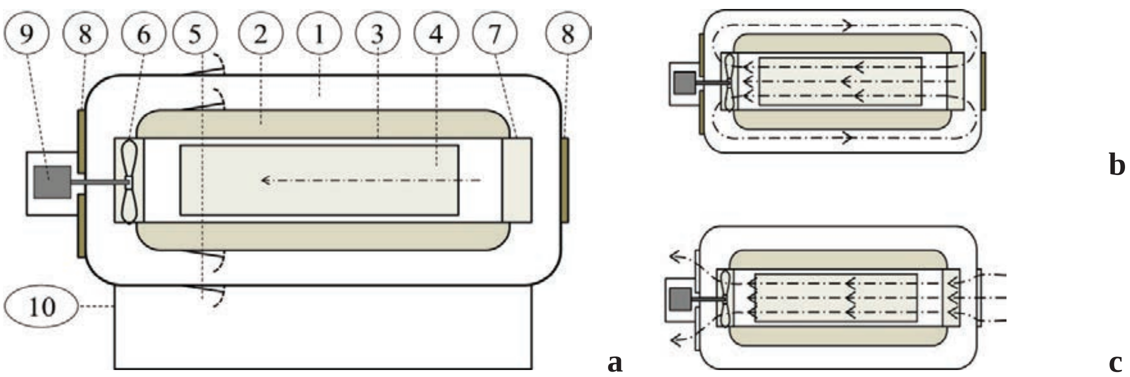
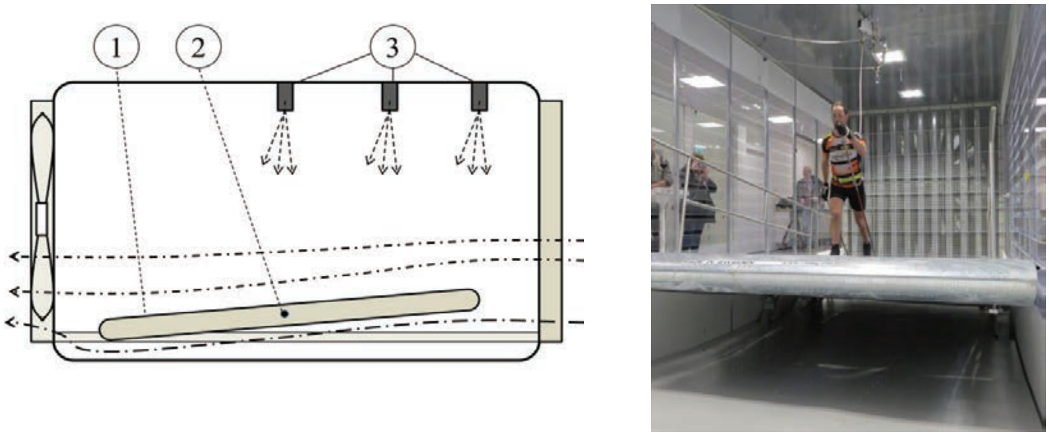


Fig. 1.Schematic diagram of(a) the Wind Tunnel Laboratory, air flow with (b) closed return and (c)atmospheric inletconfiguration of the wind tunnel.

a b c

Fig. 2. Flow straightener (a) and fan (b) as seen from the air return channel; (c) view from the "calm corridor" through the inner Lexan wall



a b

Fig. 3. (a) Pivoting (2) of the treadmill (1) and sprinkler (3) position; (b) treadmill is tested in the "uphill' configuration (view from the flow straightener side)

is formed by the inner walls (3) through a honeycomb flow straightener (7) and is actively pulled by a fan (6). The pulling fan configuration helps to decrease air turbulence inside the test section. The working area, housing a test section and two calm corridors, is smaller and lower than the inner part of the housing. Therefore, in the closed return circuit configuration, when the outer ports (8) are closed, the air is returned both around (1) and above the working part of the tunnel (Fig. 1b). The outer ports (8) in the housing can be opened, forcing the wind tunnel to work in the atmospheric inlet configuration (Fig. 1c). Built-in doors (5) allow easy access to two "calm corridors" (2) on both sides of the "wind area", the wind tunnel and the moving belt (4). The fan driving motor is placed in a separate housing (9) outside the main building to reduce noise and provide better cooling. The Lexan walls separating the test section from the "calm area", contain multiple slots (Fig. 2c) allowing to pass the cabling, pipes and objectives of motion capture and infrared cameras. Due to a small degree of air turbulence, the presence of slots elongated in the wind direction does not lead to serious disturbances inside either the "calm corridor" or the main test section.

To provide larger deflection angles for up- and downhill conditions, the moving belt system is pivoted at its middle (Fig. 3a). Air is also passed partly underneath the moving belt system (Fig 3a, b) providing lower flow turbulence near the upper moving belt surface. Water sprinklers placed on the middle to front section of the ceiling covering the wind area have a regulated water flow capable of generating anything from fine mist to monsoon-like conditions. The moving belt and test section are constructed using special materials to accommodate the elevated humidity and presence of water.

Wind and moving belt speeds can be adjusted separately or to match each other. A few reinforced beams are incorporated into the ceiling of the test section to connect to safety devices (e.g. a safety harness- visible in Figs. 2c and 3b) and load cells to stop the moving belt in case of emergency. Light, protective railings are pivoted together with the moving belt (Fig. 3b).

3. Main parameters of the system and its elements

The wind tunnel facility described in this paper is able to offer a unique combination of a large moving belt, together with a possibility of controlling the climate inside the test by changing wind and precipitation levels. The facility incorporates an additional service area with a measurement laboratory, physiology laboratory and shower room. The main formal parameters of the wind tunnel and related equipment are given in Tables 1 and 2. Calibration and tests of the facility are under way and detailed parameters will be reported soon. The fan and moving belt can be controlled using a dedicated touch-screen panel (see Fig. 2c) or using serial communication ports. The fan control system is calibrated for setting the wind speed inside the test section by adjusting the motor control at 6 rpm increments. The moving belt speed can be regulated at 0.1 km/h increments.

Table 1. Main parameters of the wind tunnel and moving belt

Wind tunnel		**Moving belt**	
Main building dimensions	10 by 8 by 23 m^3	Working area length	5 m
Flow straightener cross-section area	10 m^2	Working area width	2.7 m
Test section cross-section area	10.5 m^2	Maximum uphill angle	19^o
Maximum air flow capacity	124 m^3/s	Maximum downhill angle	9^o
Laboratory and service area	46 m^2	Maximum speed guaranteed	55 km/h
Constructed by: A4 Campus AB, Östersund, Sweden		**Manufacturer:** Rodby Innovation AB, Uppsala, Sweden **Type:** RL5500E, Tilting	

Table 2. Main parameters of the wind tunnel construction elements

Fan		**Fan motor**		**Rain system**		**Flow straightener**	
Impeller diameter	280 cm	Axle diameter	240 mm	Flow rate	17-27 L/min	Type	Honeycomb
Maximum rotation rate	600 rpm	Power	200 kW	Intensity	0.03-0.04 L/(m^2·s)	Cell pattern	Hexagon
Efficiency	86%	Weight (motor only)	2200 kg	Muzzle velocity	5-8 m/s	Cell width	12.7 mm
Weight (fan only)	6300 kg	Weight (axel only)	2200 kg	Pressure	0.2-0.5 bar	Cell length	160 mm
Manufacturer: Howden Axial Fans AB,Växsjö, Sweden **Type**: Axicent, 280FFA/140/5010/16/20/NABD/E040		**Manufacturer:** ABB, Västerås, Sweden **Type:** ABB 355MLB 10		**Manufacturer:** BETE Fog Nozzle Inc., Greenfield, USA		**Manufacturer:** Easterline Technologies Corp., Stillington, UK	

The dimensions of the test section are strongly determined by the dimensions of the moving belt and the diameter of the fan. In our case, the moving belt system was designed and constructed specifically for the current project and is among the largest in the world. The belt has a working area which is 2.7 m wide and 5.5 m long with adjustable elevation angles ranging from -9^o (downhill) to +19^o. The belt is one of the fastest among the belts of comparable size (See Table 1). So far, the moving belt (treadmill) is the largest that has been constructed by Rodby AB [3].

To the best of our knowledge, only a few moving belts functioning today are larger than the one described. According to the Guinness Book of Records the largest moving belt in the world opened in September 2004 was built for the purpose of a Discovery Channel television show. It has a working area 7.32 m long 3.37 m wide and a top speed of 32.2 km/h. It has an adjustable elevation angle which can be set to +20^o [4]. Another moving belt which has appeared in the news in November 2014 was made as a show item by the Chilean company Oxford Fitness. It measures 6.0 m by 3.0 m (another source gives 9.08 m by 3.66 m and it is unclear if these dimensions represent its working area) and has a top speed of 16.1 km/h [5]. No information is available if this moving belt has adjustable elevation angles. An even longer moving belt measuring 2.5 by 10 m was made in a zoo for keeping wolves fit [6]. Another moving belt was installed at the In2Ski Indoor Snow Sports Centre in Alexandria, Sydney [7] having working area 5 m by 9 m. It was used for indoor downhill skiing. Unfortunately this facility is now closed.

Climate-controlled wind tunnels are commonly constructed forth aerospace and automotive technology research and development. Such facilities exist for example at Audi and BMW (Germany), SAAB-Scania (Sweden) as well as within academia - for example at the Norwegian University of Science and Technology (Norway), Eindhoven Technical University (The Netherlands), University of Ontario (Canada), Italian Aerospace Research Centre (CIRA, Italy), Monash University (USA) and many more. Some similar facilities are oriented towards the needs of the construction industry such as one of the largest climatic wind tunnels Jules Verne (CSTB Nantes, France) and the one used by Building Product Design (UK). Many of these facilities are also used for sports technology research and related development work.

At the moment, the capacity of our wind tunnel climatic control system is rather limited. Given current settings, our facility can only provide a controlled air temperature in the range of about +4 to +35 ^{o}C with a limited ability to control humidity (in the closed return circuit configuration). However, by opening the port doors and letting the outer air in, the inside of the facility can easily accommodate temperatures below freezing from November until the best part of April. Currently, the ability to do so depends on potentially unstable weather. However, in the near future, we plan to significantly increase the capacity of the built-in climate control system. There is also a unique possibility of having mist and rain in our wind tunnel system (Fig. 4a, b), but which consequences these might have for the temperature and humidity control should be further studied in detail.

a **b** **c**

Fig. 4. (a) Walking in the rain: Rector and Deputy Rector of Mid Sweden University are officially opening the facility on March 23, 2015; (b) testing the fast uphill roller-skiing with heavy rainfall; (c) testing the downhill motion in presence of matching treadmill and wind speeds

4. Ongoing and planned research and development work

The main areas of research, development and educational activities of the Sports Tech Research Centre at Mid Sweden University are biomechanics and performance optimization; human and equipment interaction and sports technology for the disabled [8-13]. Significant attention is devoted to cooperation with local and national industry, in particular operating in the sports and outdoor clothing, footwear and equipment. Therefore, at the moment, we plan to concentrate on the research areas described below (though we plan to widen the scope of our activities with the help of our partners in the future).

Winter sports research and development is one of our traditional areas which we hope to improve using the new facilities [8-11]. Among our primary interests are roller-ski related studies covering rolling resistance, bearing resistance, new roller ski elements and constructions [10], vibrations in equipment [8, 9], the effect of posture on performance, equipment related physiology aspects and training, and garment design. Studies of the aerodynamics of individual skiers and the effects of different skier formations (slipstreaming, drafting) will also be carried out. It is known that roller skiing “downhill” on the moving belt in presence of generated wind represents real skiing much better due to the presence of adequate air drag [1, 2]. This was immediately noticed by elite skiers during the very first wind tunnel tests (Fig. 4c). In relation to biathlon, we also plan to study different training procedures, especially related to aiming and rifle stability in the presence of wind and continue developing corresponding hardware for measurements and training support. Together with Sufag (Östersund, Sweden) we are also developing sprinkler system for generating fine mist and snow inside the test section.

Bicycle related research and development is another of the primary areas of our interest, especially in relation to testing and validating performance, and pacing strategy optimization algorithms for competitions carried out in variable terrain and different ambient temperature and wind conditions [11]. The wind tunnel facility will also be used in support of developing new equipment and in testing and comparing different constructions of major bicycle elements (wheels, frames) and complete bicycles. Another wide research field studies how cyclist performance and stability is affected by hardware construction, posture, yaw angle, rain and wind conditions. With additional equipment it will be possible to study the effects of vibrations and the mechanisms of their onset in bicycles. Two tree-axis force plates by Kistler which could be installed either under the rubber belt or above it on a special rig will be used to record reaction and drag forces.

Equipment for disability sports is another important area of research and development at Mid Sweden University [12, 13]. Equipment plays a central role for people with physical impairment in being able to live an active life through exercise, sports and outdoor activities. Such equipment is commonly individualized and may range in complexity from simple to extreme. The issue of properly designing such equipment is quite acute today. Even more pressing is being able to assure that fair and equal circumstances are achieved in competitions and that all disabled athletes as well as the general public have fair access to modern technology. We will be developing a few particular directions in the near future. One of our long-term aims is to incorporate the wind tunnel facility and the expertise of researchers working there into the international network supporting the Paralympics movement. One of the possibilities is through assisting in the knowledge transfer for improving the classification systems in Para sports, for example through full body motion simulations based on motion capture and other experimental data. Another direction is related to the evaluation of air resistance and wind/rain influence upon equipment and garments used by disabled people in skiing, hand cycling and using wheelchairs of different construction. One more direction of high social importance is the individualization of support equipment, and adaptation of new equipment to a person with impairment. This research will benefit from all advanced knowledge in sports technology and sports science, from 3D motion capture and gait analysis to advanced modeling and development of training and rehabilitation protocols, and advanced quantification of progress. An additional asset for such research is our existing knowledge and facilities related to 3D printing in polymers and metals.

Training, rehabilitation and injury prevention related research is designed to benefit all people, able-bodied and disabled, athletes and the general population. A combination of the moving belt and precipitation control with advanced measurement and motion capture equipment, easy communication with trainees from the calm corridor of the facility, where the support personnel will be, transparent walls of the tunnel and its surroundings, making it much less claustrophobic (Fig. 4c) and measurement equipment and infrastructure all provide a big asset for developing training and rehabilitation programs. Planned incorporation of virtual reality systems will also provide an additional degree of realism to the training and rehabilitation process. Advanced studies of the equipment-related biophysics of sports and exercising will be carried out benefiting all research aspects related to the wind tunnel work. Work on injury prevention will incorporate both equipment development and advanced testing and, to significant extent, also the validation of mathematical models and development of training protocols and recommendations.

Sports and outdoor equipment development and tests are our traditional areas of interest. Here we work in tight cooperation with different corporate partners. A unique combination of the moving belt, wind and climate controls together with advanced sensorics and measurement technology allows assessing the interaction of garments, footwear and equipment with human subjects under conditions which are close to reality and at the same time controlled in a flexible manner. This allows breaching a gap between the objective assessment of mathematical models, construction elements (ropes, fasteners, fabrics, polymeric and metallic materials), equipment items (footwear, jackets, bags, tents, wheelchairs, bicycles, skis, helmets) and all in combination with human subjects. In addition, advanced field sensor testing and validation work will also be carried out. This work will also demand further expansion in measurement and data acquisition technology along with the development of advanced test protocols.

Wind tunnel facility development plans incorporate three major directions: further development of existing hardware, increasing data transfer and handling capacity and incorporating elements of virtual reality. Near future plans for related hardware include the installation of a 3D motion capture system, multiple monitoring infrared cameras and increasing the capacity of the climate control system. Although, each of these tasks separately is not extraordinarily complex, incorporation of these features into the existing facility without degrading its parameters will be quite challenging. As the test section of the facility has a large cross section area, wind speeds are not adequate for some experiments even with the significant power and capacity of the fan system [2]. Therefore, experiments will be carried out by narrowing the test section using additional temporary mounted panels, aiming at higher wind speeds for studying alpine skiing, speed biking and similar experiments. Installation of air flow visualization (“smoke generators”) and advanced measurement systems is also planned.

An advanced computer system is currently installed to satisfy the needs of multiple control and data acquisition systems related to the wind tunnel. The basic design of the system is already prepared for this with all major elements like the moving belt system, fan and climate control units having their own advanced controllers that can be accessed by an external computer through serial communication ports. Overall data acquisition and control will be carried out using National Instruments’ LabVIEW software. All these elements are complex but separately not unique. A greater challenge is being able to allow a freedom of motion to the objects on the moving belt together with a stable transfer of data from the sensors mounted on the body, garments and equipment. Among the possible solutions currently being considered are single cable or optical fibre- based systems, and systems based on multiple wireless nodes.

Virtual reality (VR) systems are known to add exceptional realism to the activities humans can carry out in a simulated environment. However, it is not possible to install panoramic or even large size monitors or projection screens in the wind tunnel without disturbing the air flow. Thus one of the few possible solutions is to use goggle-based VR systems. Linked to the advanced controls of the moving belt and wind, the VR system can provide ideal support to the training and rehabilitation process. For example, one will be able to run the Olympic or World championship track (athletics, skiing or biathlon) and compare one’s own results of consecutive laps with the results shown by other athletes. Biathlon training can incorporate virtual reality target shooting with a simultaneous monitoring center of pressure dynamics, hand and rifle motion, breathing patterns, heart rate, perspiration and so on.

5. In summary

This paper outlines the results of the early steps in the Mid Sweden University Sports Tech Research Centrewind tunnel project and describes the near future plans for the related activities we have already put forward. More detailed publications describing the facility parameters and its calibration and verification are already under way. One of the main aims with this paper is to invite the wider Sports Technology and Sports Science community to cooperate on and participate in research and development carried out at the wind tunnel facility offering a unique combination of large a fast moving belt as well as wind and climate controls.

Acknowledgements

The design and construction of the Mid Sweden University Sports Tech Research Centre wind tunnel was a joint effort supported by numerous people and organizations. We are thankful to all of them, though the format of this paper does not even allow us to produce a full list. The construction project was financially supported by Mid Sweden University, the Swedish Agency for Economic and Regional Growth (Tillväxtverket) and Östersund municipality. The moving belt system was financed by the European Union European Regional Development Fund through the “Focus Outdoor” Project. We are also grateful to our colleagues from Loughborough University for their assistance.

References

[1] Barelle C. Sport Aerodynamics: on the Relevance of Aerodynamic Force Modelling versus Wind Tunnel Testing. In: Lerner JC editor. Wind Tunnels and Experimental Fluid Dynamics Research. InTech; 2011 under CC BY-NC-SA 3.0 license

[2] Oggiano L. Drag reduction and aerodynamic performances in Olympic sports. PhD Thesis, NTNU, Trondheim 2010, 187 pages.

[3] http://www.rodby.com/products/treadmills/

[4] Guinness book of records. http://www.guinnessworldrecords.com/world-records/largest-treadmill

[5] http://www.dailymail.co.uk/sciencetech/article-2842940/No-room-gym-giant-running-machine-space-TEN-runners-once.html

[6] http://blogs.scientificamerican.com/dog-spies/why-the-world-s-longest-treadmill-was-created-for-wolves/

[7] http://in2ski.com.au/

[8] Koptyug A, Ainegren M. Experimental measurement of rifle dynamics during the range shooting of biathlon weapons. Procedia Eng. 2015; 112: 349 -354.

[9] Koptyug A, Bäckström M, Tinnsten M, Carlsson P. Cross-country ski vibrations and possible mechanisms of their influence on the free gliding. Procedia Eng. 2012; 34: 473-478.

[10] Ainegren M, Carlsson P, Tinnsten M. Roller ski rolling resistance and its effects on elite athletes’ performance. Sports Eng. 2009; 11: 143-157.

[11] Sundström D, Carlsson P, Tinnsten M. Comparing bioenergetic models for the optimisation of pacing strategy in road cycling. Sports Eng. 2014; 17: 1-9.

[12] Elmer S, Danvind J, Holmberg H-C. Development of a novel eccentric arm cycle ergometer for training the upper body. Medicine & Science in Sports & Exercise. 2013; 45: 206-211.

[13] Holmberg J, Lund Ohlsson M, Danvind J. Musculoskeletal simulations: a complementary tool for classification of athletes with physical impairments. Prosthetics and orthotics international 2012; 36: 396-397.